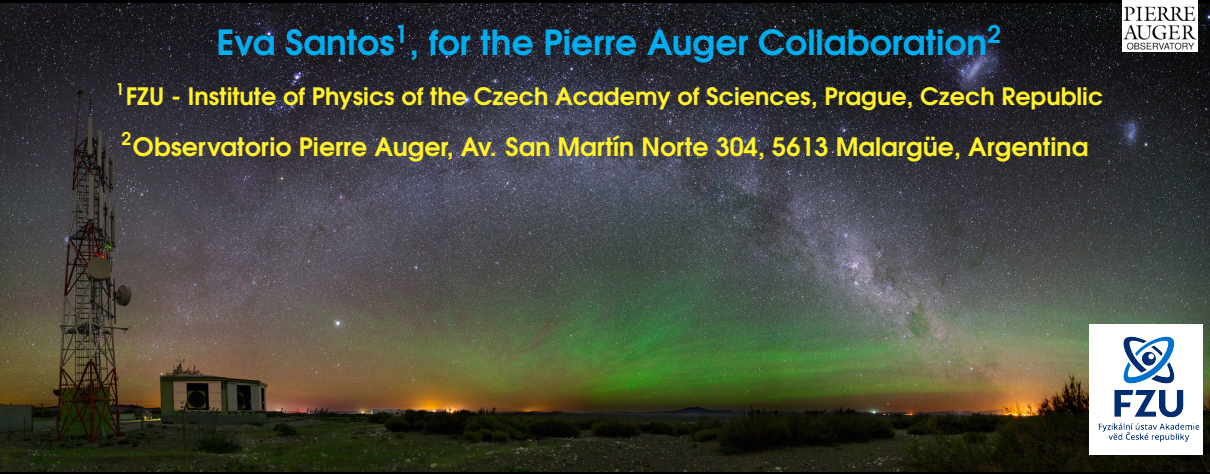
Highlights of the Pierre Auger Observatory

Eva Santos[1], for the Pierre Auger Collaboration[2]

[1]FZU - Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

[2]Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina



HEP2023 - VIII International Conference on High-Energy Physics in the LHC Era

Valparaíso, Chile, 9th - 13th January 2023

Outline

- **Motivation**
- **Introduction to ultrahigh-energy cosmic rays**
- **Pierre Auger Observatory**
- **Pierre Auger Collaboration results**
  - Spectrum
  - Anisotropy searches – **See talk tomorrow by J. de Mello Neto**
  - Nuclear mass composition
  - Hadronic interactions – **See talk tomorrow by B. Andrada**
  - Neutral particles
    - Ultrahigh-energy photons and neutrinos
  - Multimessenger studies
- **AugerPrime**

Motivation

- **Cosmic rays are the most energetic particles in the Universe**
  - Can exceed energies of 10^{20} eV ($E \sim 16$ J or $\sim 10^{23}$ K!)
    - Same energy of a tennis ball served at 100 km h^{-1}
    - We would need a particle accelerator with the size of the orbit of Mercury
- Origin, nature and acceleration of the highest energy cosmic rays is still unknown
  - Less than one particle per km^2 per century for $E > 5 \times 10^{19}$ eV

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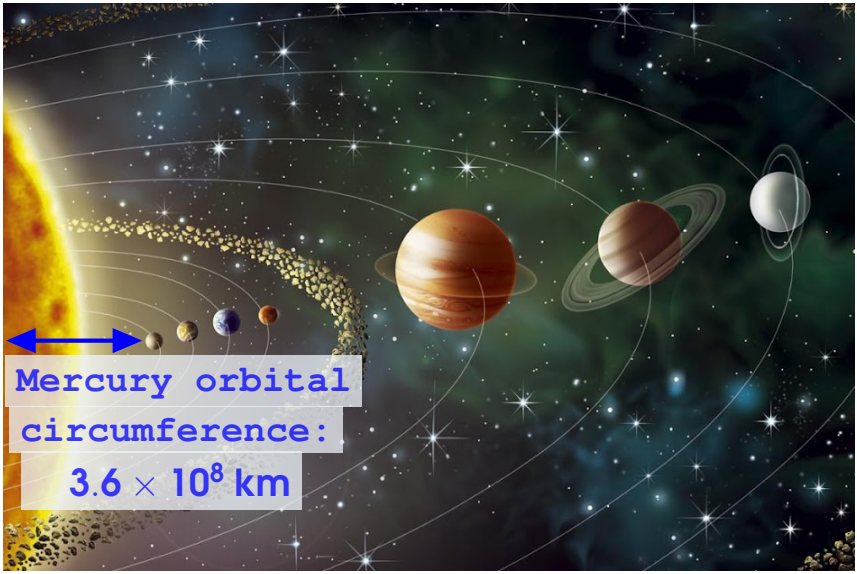

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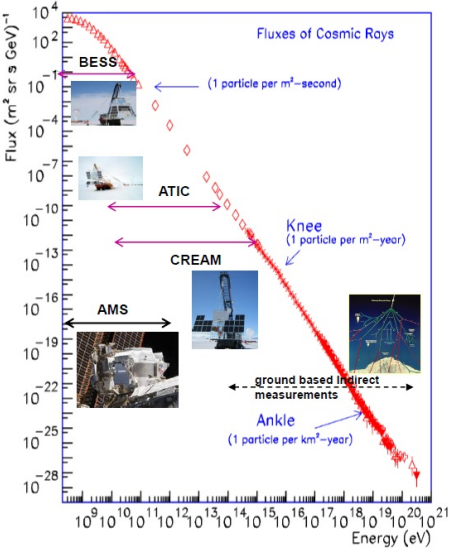
We need $\sim 1000\,km^2$ detector areas!

Cosmic Ray Spectrum



Credits: ISS-CREAM

Cosmic rays are mostly fully ionized atomic nuclei

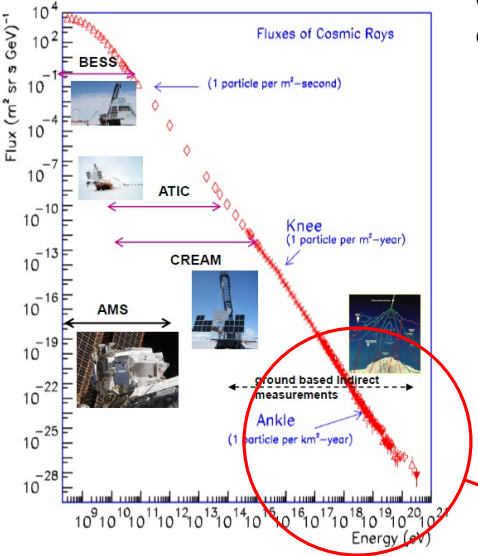
- Most are protons, but almost all stable elements may be found

"Almost" featureless power law spectrum:

$$\frac{dN}{dE} \propto E^{-\gamma}$$

- $>$ 10 decades in energy
- $>$ 30 orders of magnitude in flux
- 3 main spectral features

Cosmic Ray Spectrum



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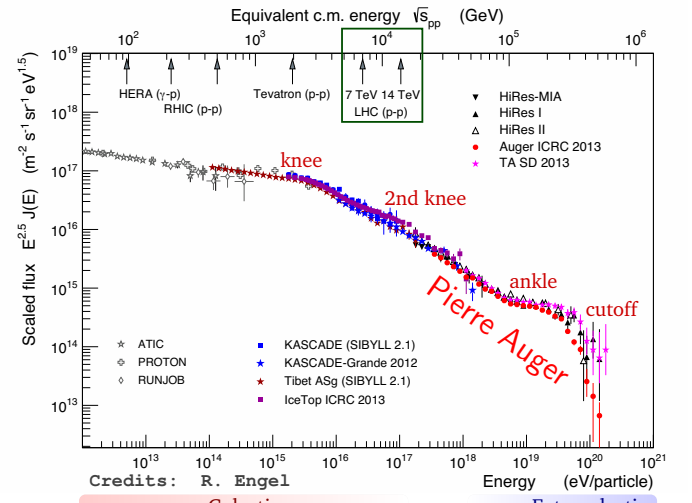
Pierre Auger Observatory

Cosmic Ray Spectrum - Scaled

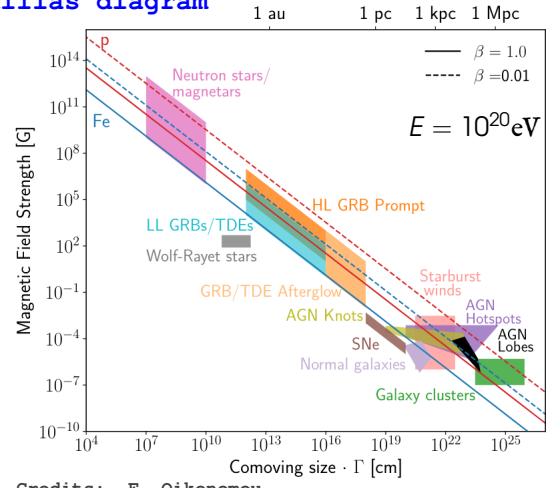
E_{lab} up to 10^7 times larger than at the LHC, flux $\approx$ 1 part/km^2/year at 10^{19} eV



Ultrahigh-Energy Cosmic Ray Source Candidates

Origin and acceleration processes are still unknown...

Hillas diagram

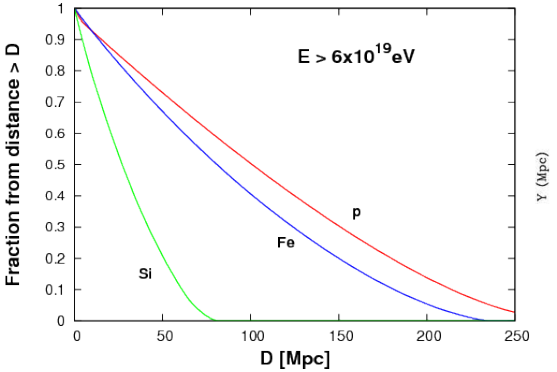


Credits: F. Oikonomou

A. M. Hillas, Annual Review of Astronomy and Astrophysics, vol. 22 (1984)

Ultrahigh-Energy Cosmic Ray Origin and Propagation

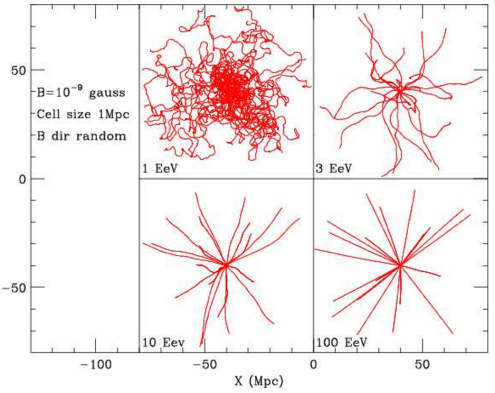
Highest energy cosmic rays must come from nearby ($\lesssim$ 300 Mpc) sources



D. Harari, Comptes Rendus Physique 15 (2014)

Protons emanating from a point source

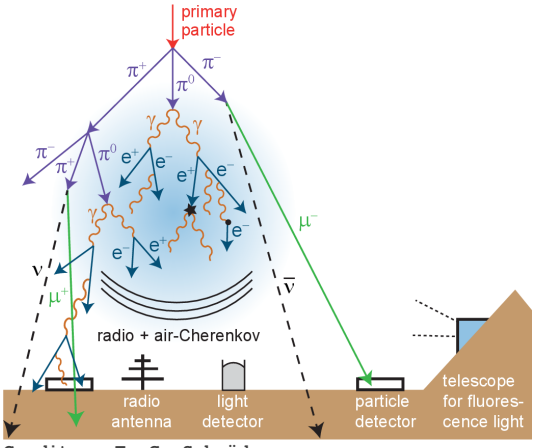
3D trajectories projected on X−Y plane



Credits: J. Cronin

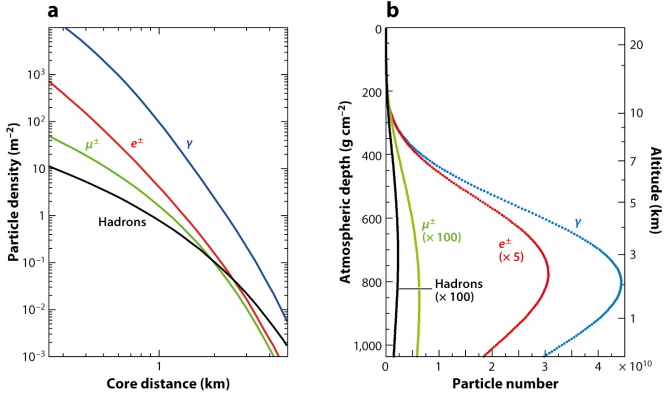
Arrival directions of cosmic rays $\leftrightarrows$ Nuclear mass composition

Extensive air showers



Credits: F. G. Schröder

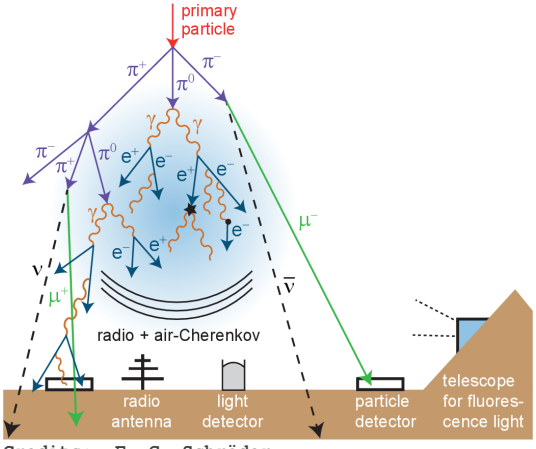
Vertical 10^{19} eV proton shower
Particle lateral distributions at 870 g cm^{-2}



Engel R, et al. 2011.
Annu Rev. Nucl. Part. Sci. 61:467–89

Electromagnetic longitudinal shower profile

Our best estimator of the mass composition of cosmic rays



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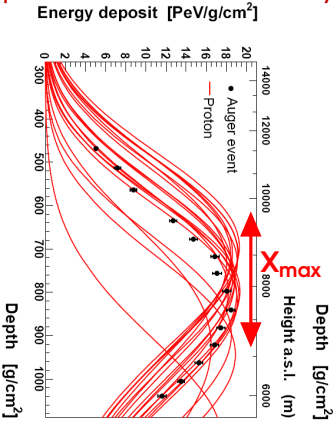
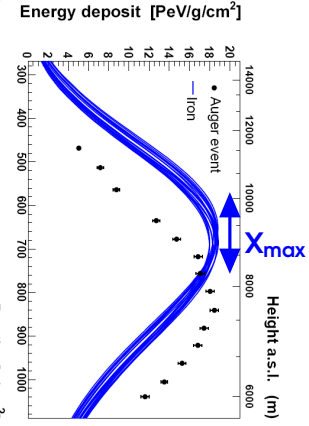


Proton initiated showers



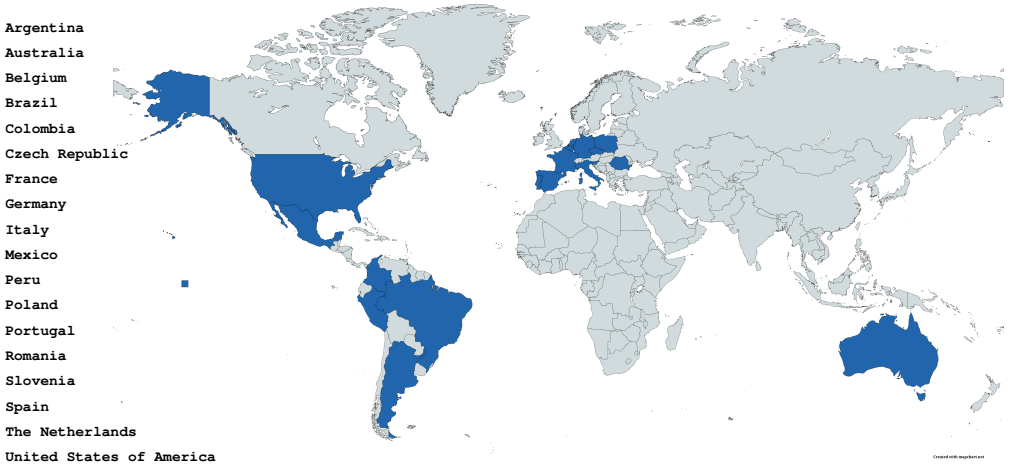
Iron initiated showers

- $\sim 100\,\mathrm{g\,cm^{-2}}$ deeper $\langle X_{\max} \rangle$
- $\sim 3\times$ larger $\sigma\,(X_{\max})$

Pierre Auger Observatory

Pierre Auger Collaboration

About 400 authors from nearly 100 institutes from 18 countries



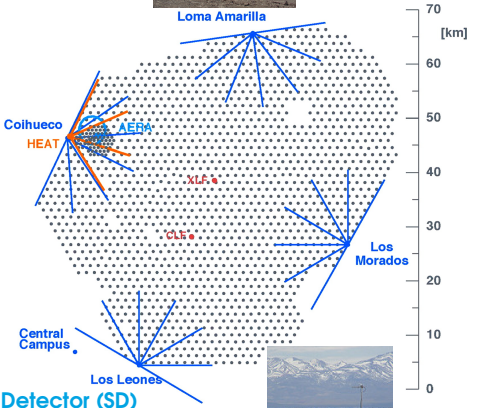
Pierre Auger Observatory

Malargüe, Province of Mendoza, Argentina

35.2° *S*, 69.5° *W*, ∼ 1400 m a.s.l.

Fluorescence Detector (FD)

- 27 Schmidt telescopes
- ∼ 15% duty cycle

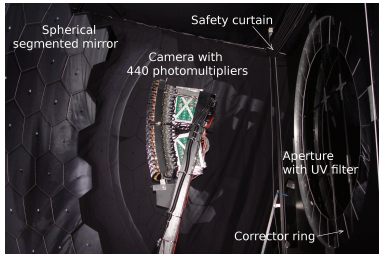


Surface Detector (SD)

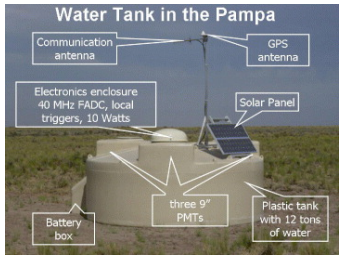
- 3000 km^2
- 1660 Water Cherenkov Detectors
- ∼ 100% duty cycle

A hybrid detector

Fluorescence Detector



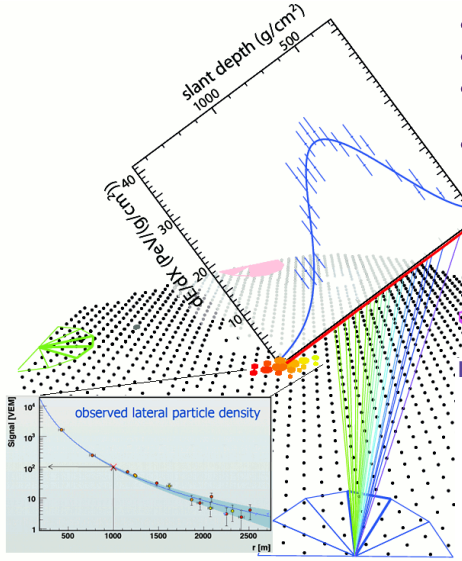
Surface Detector station



A hybrid detector (II)

Fluorescence Detector

- Longitudinal shower profile
- Electromagnetic component
- Quasi-calorimetric energy estimation
- Direct $X_{\max}$ measurement



Surface Detector array

- Lateral particle distribution
- Electrons, muons, high-energy photons
- High statistics

Hybrid events

- Observed by both detectors
- "Golden hybrid" events used for SD array energy calibration
- Higher shower detection accuracy

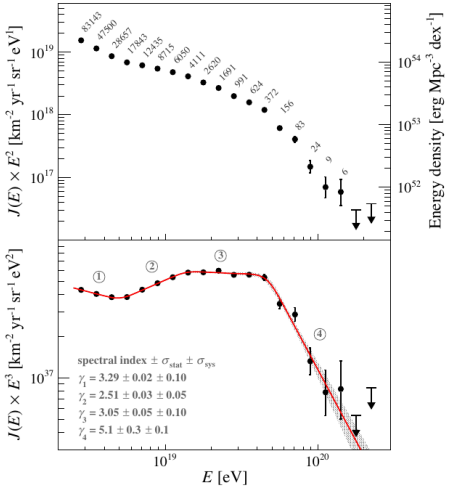
Highlights from the Pierre Auger Collaboration

Spectrum measurements

Energy spectrum of cosmic rays at $E > 2.5 \times 10^{18}$ eV

The "instep" - A new spectral feature was discovered!

Editor's Suggestion



Data set:

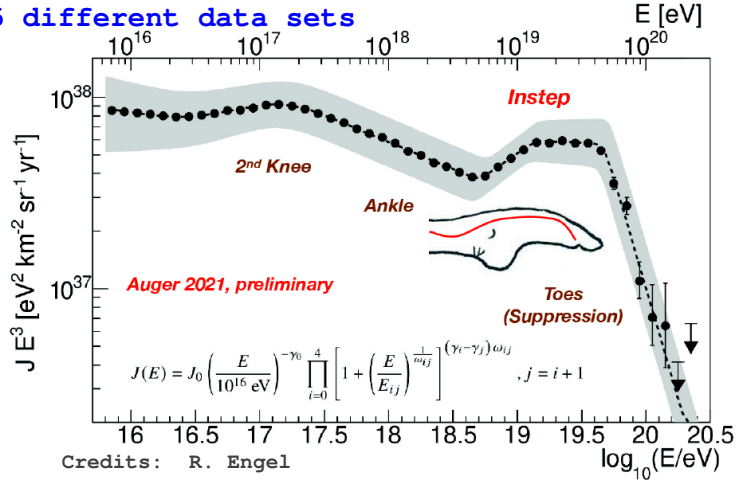
- 1 January 2004 - 31 August 2018
- 215030 SD events
- $E > 2.5$ EeV
- $\theta < 60°$
- 60400 km^2 sr yr exposure

parameter	value $\pm\sigma_{stat} \pm \sigma_{sys.}$
J_0 [km^{-2} sr^{-1} yr^{-1} eV^{-1}]	$(1.315 \pm 0.004 \pm 0.400) \times 10^{-18}$
γ_1	$3.29 \pm 0.02 \pm 0.10$
γ_2	$2.51 \pm 0.03 \pm 0.05$
γ_3	$3.05 \pm 0.05 \pm 0.10$
γ_4	$5.1 \pm 0.3 \pm 0.1$
E_{12} [eV] (ankle)	$(5.0 \pm 0.1 \pm 0.8) \times 10^{18}$
E_{23} [eV]	$(13 \pm 1 \pm 2) \times 10^{18}$
E_{34} [eV] (suppression)	$(46 \pm 3 \pm 6) \times 10^{18}$
D/n_{dof}	17.0/12

Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D 102 (2020) 062005

Energy spectrum of cosmic rays from $E > 6 \times 10^{15}$ eV

Combined Auger wide-energy spectrum



Eur. Phys. J. C 81 (2021) 966
PoS(ICRC2021), 324 (2021)

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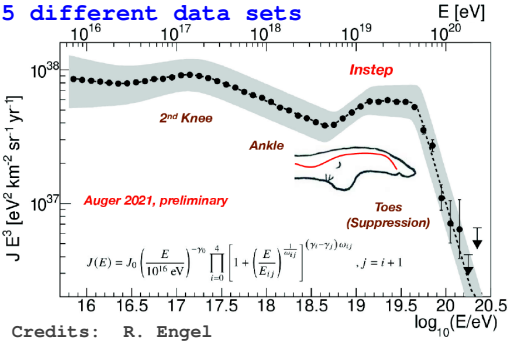

Credits: R. Engel

- Coverage $\sim$ 5 decades in energy in one experiment
- Low-energy ankle at 2.8×10^{16} eV reported for the first time
- Discovery of the "instep" feature at 1.4×10^{19} eV
  - It's existence was later confirmed by the Telescope Array experiment

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km^{-2}sr^{-1}yr^{-1}eV^{-1}

		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
low energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV	$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
2nd knee	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV	$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV	$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
instep	$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV	$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
suppression	$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV	$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

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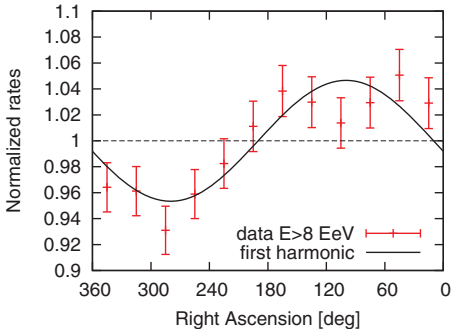
Anisotropy searches

Observation of large scale anisotropy for $E > 8$ EeV



Data set:

- 113888 SD events
- $E > 4$ EeV
- 1 January 2004 - 31 August 2016
- 76800 km^2 sr yr exposure
- $\theta < 80°$
  - $-90° < \delta < 45°$ (85% sky)

Nearly uniform exposure in Right Ascension => High sensitivity to flux modulation

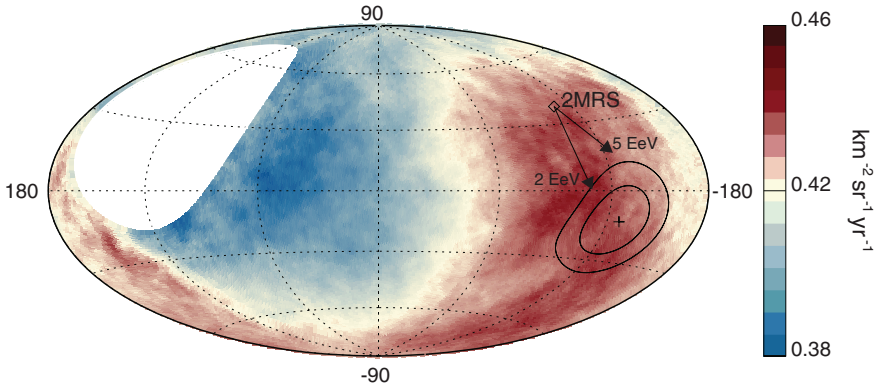
Energy (EeV)	Number of events	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	$0.005\ ^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	$0.047\ ^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

5.6 σ away from isotropy!

Science 357 (2017) 1266–1270

Observation of large scale anisotropy for $E > 8$ EeV (II)

Highest energy cosmic rays have extragalactic origin!

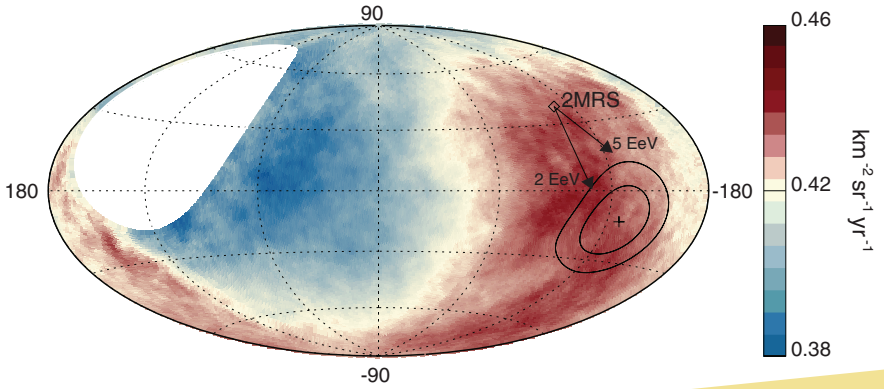


- Dipole became more significant with increasing exposure
- Maximum modulation at Galactic Coordinates $(l, b) = (233°, -13°)$
  - $\sim 55°$ away from the 2MRS dipole

Science 357 (2017) 1266–1270

Observation of large scale anisotropy for $E > 8$ EeV (II)

Highest energy cosmic rays have extragalactic origin!



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See talk tomorrow by:
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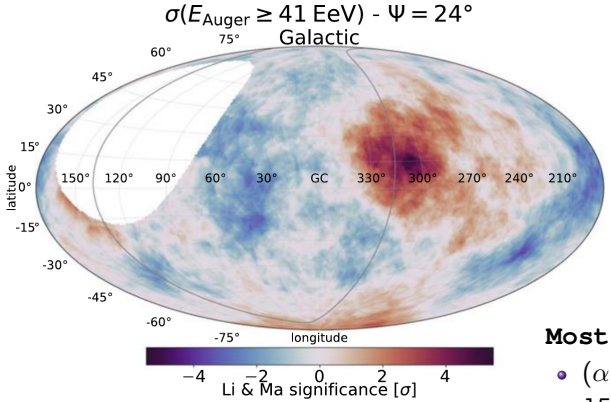
Anisotropy searches at $E > 32$ EeV from Auger Phase I

Searches for localized excesses of Ultrahigh-Energy Cosmic Rays



Blind search:
No correlation with **any** source candidates

Data set:

- 2635 SD events
- $E \geq 32$ EeV
- 1 January 2004 - 31 December 2020
- 122000 km^2 sr yr integrated exposure
- $\theta < 80°$
  - $-90° < \delta < 45°$ (85% sky)

Most significant excess from isotropy:

- $(\alpha, \delta) = (196°.3, -46°.6)$ / $(l, b) = (305°.4, 16°.2)$
- 153 / 97.7 observed / expected events
- 5.4σ local Li-Ma significance
- 3% p-value - post-trial

The Astrophysical Journal 935 (2022) 170

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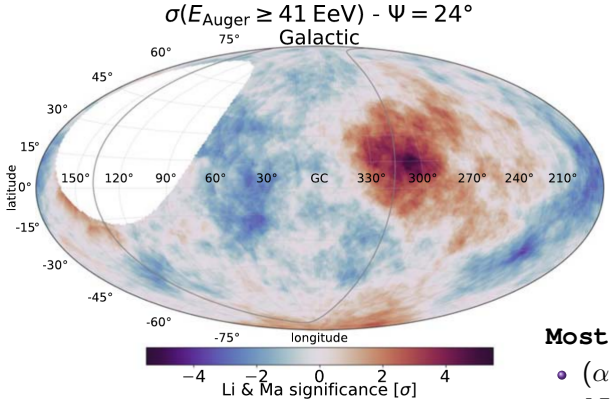

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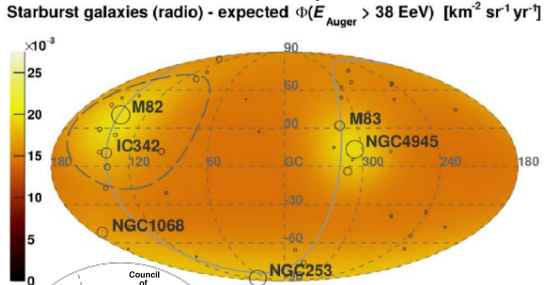
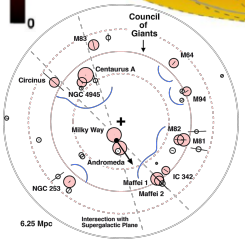
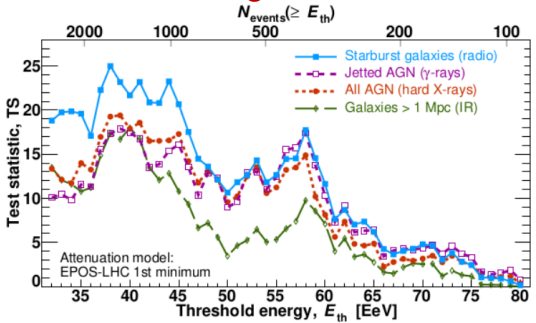
Correlation of anisotropies with source candidate catalogs







Hotspot in Cen A region dominates anisotropy signal:

- Starburst galaxies:
  - 4.2σ departure from isotropy at $E > 38$ EeV
- AGNs:
  - 3.3σ departure from isotropy at $E > 39$ EeV

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Astrophys. J. Lett. 853 (2018) L29

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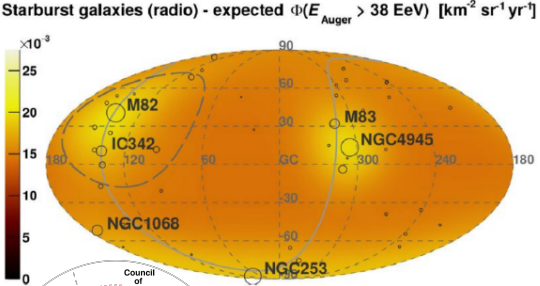
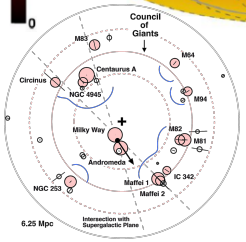
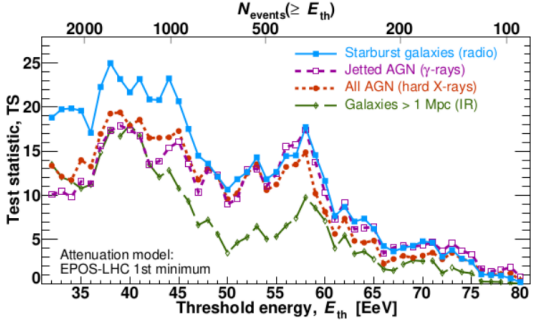






Hotspot in Cen A region dominates anisotropy signal:

- Starburst galaxies:
  - 4.2σ departure from isotropy at E
- AGNs:
  - 3.3σ departure from isotropy at E

See talk tomorrow by:
João de Mello Neto

The Astrophysical Journal 935 (2022) 170
Astrophys. J. Lett. 853 (2018) L29

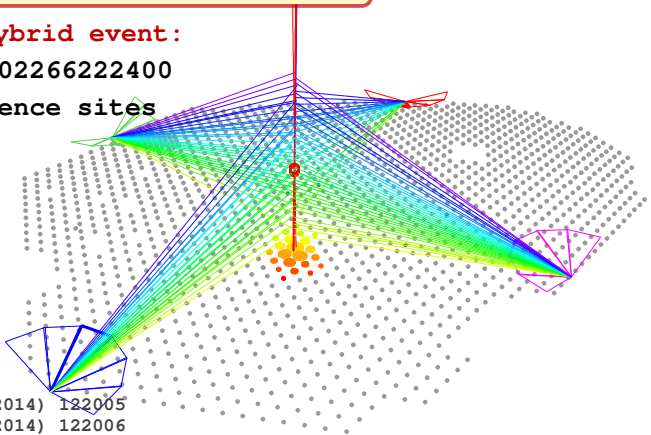
Nuclear mass composition

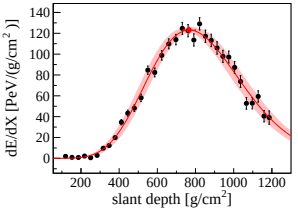
Measurement of the depth of the shower maximum X_{max}

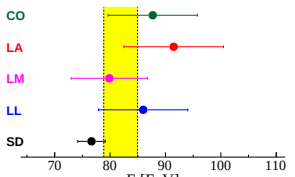
- **47863 high-quality events**
- **1020 events with $E > 10$ EeV**
- **Highest energy: $E = 104 \pm 9.5$ EeV**

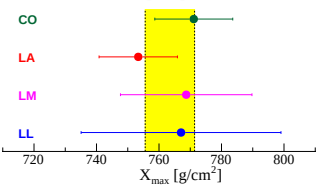
Real Auger Hybrid event:

- **Event ID 102266222400**
- **4 fluorescence sites**



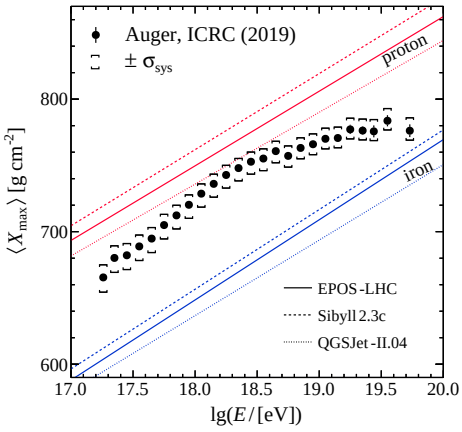


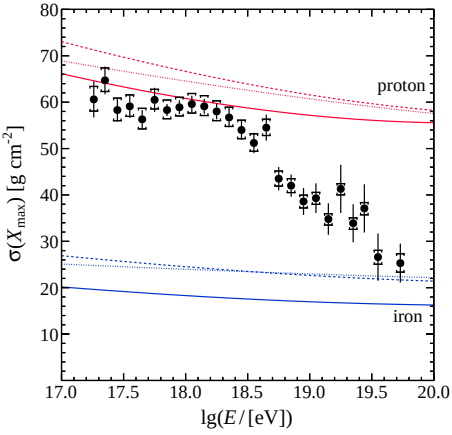




Phys. Rev. D 90 (2014) 122005
Phys. Rev. D 90 (2014) 122006

Energy evolution of the mean and standard deviation of $X_{\max}$





- **Trend from heavier to lighter mass composition up to $10^{18.3}$ eV (2 EeV)...**
  ... and towards heavier composition afterwards
- **Hardening of the all-particle cosmic ray spectrum ("ankle") at 5 EeV**

Energy evolution of fractions of primary nuclei

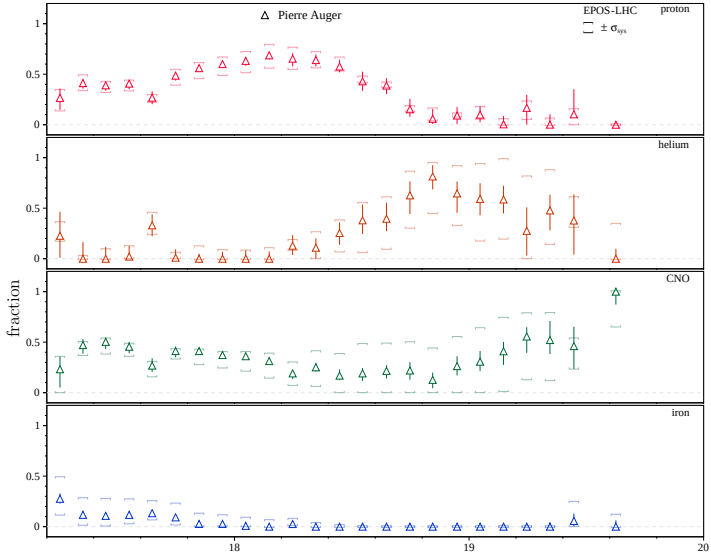


Figure: A. Yushkov

PoS(ICRC2017), 506, (2017)

Energy evolution of fractions of primary nuclei

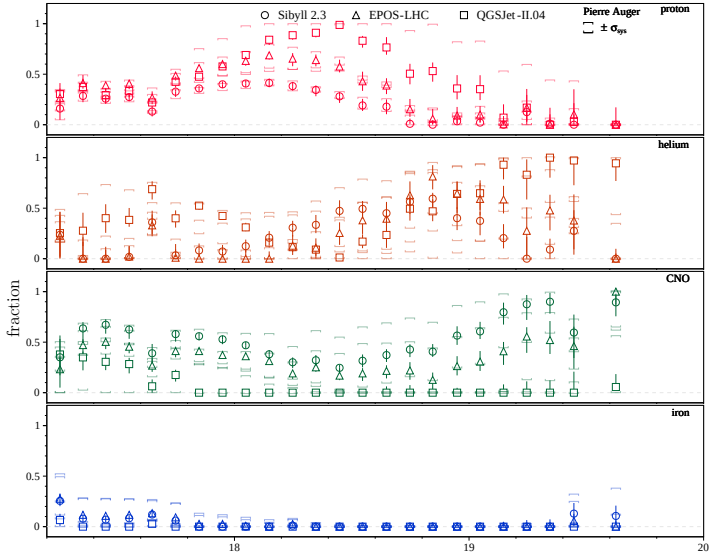
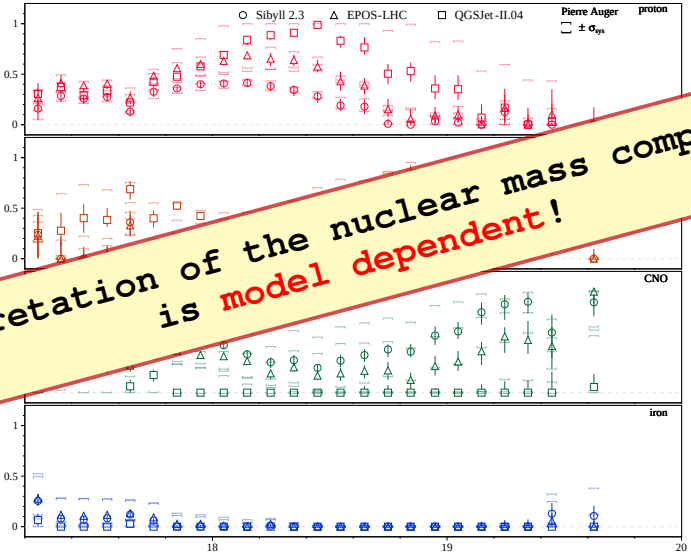


Figure: A. Yushkov

PoS(ICRC2017), 506, (2017)

Energy evolution of fractions of primary nuclei



Interpretation of the nuclear mass composition is model dependent!

Figure: A. Yushkov

PoS(ICRC2017), 506, (2017)

Extension of X_{max} measurements up to 10^{20} eV using SD data

100% duty cycle - 30 $\times$ more statistics than the FD!

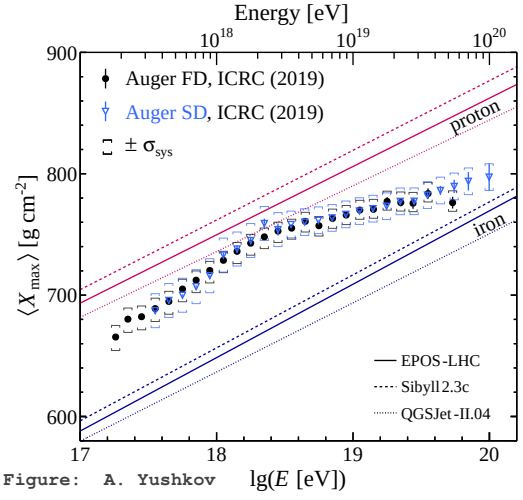


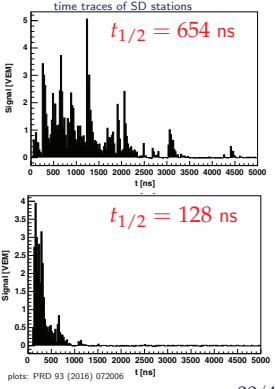
Figure: A. Yushkov

Phys. Rev. D 96 (2017) 122003
PoS(ICRC2019), 440, (2019)

Data set:

- 125005 SD events
- $E > 3$ EeV
- 1 January 2004 - 31 August 2018
- $\theta < 60°$

SD station FADC traces



Extension of X_{max} measurements using radio data

Auger Engineering Radio Array

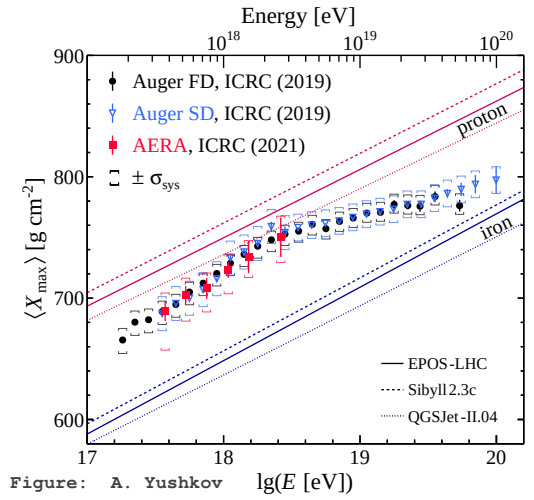
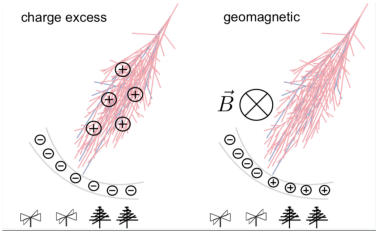
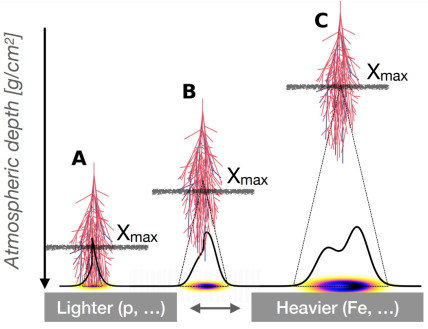


Figure: A. Yushkov

Data set:

- 2153 high-quality AERA events
- 0.1 - 10 EeV
- 7 years of data
- $\theta < 55°$

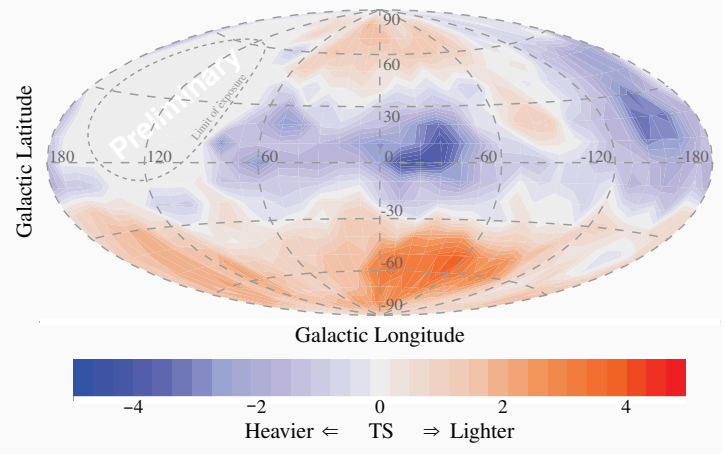


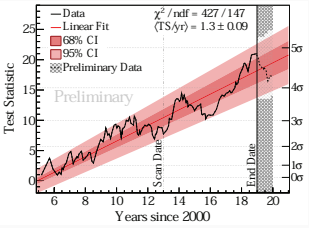


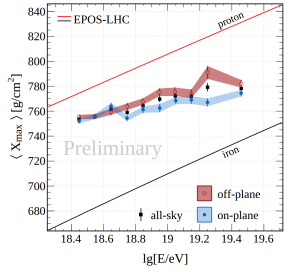
AERA station
30 - 80 MHz

Indication of mass-dependent anisotropy above $10^{18.7}$ eV

Hybrid events







Indication of a heavier composition on the Galactic Plane with 3.3σ significance (including systematic uncertainties)

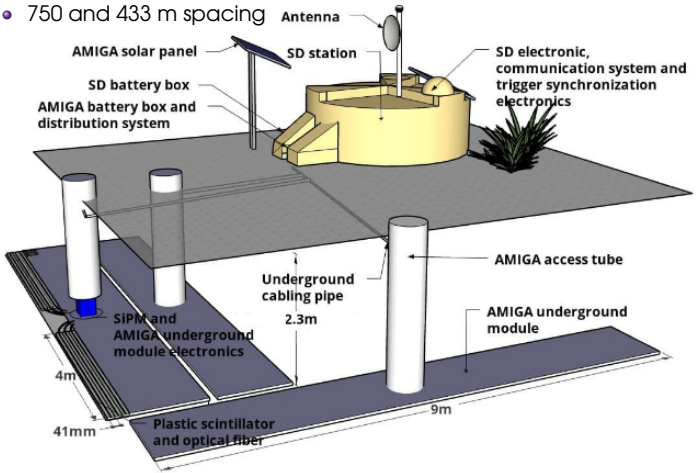
PoS(ICRC2021), 321, (2021)

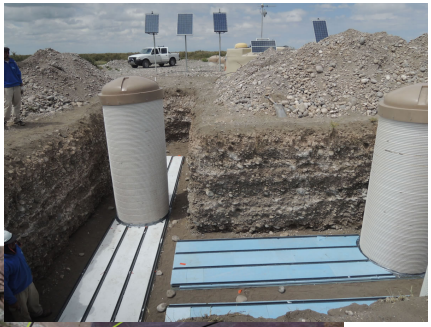
Hadronic interactions

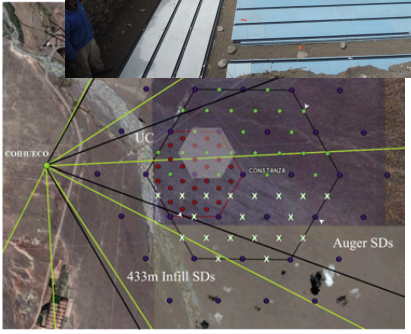
Auger Muons and Infill for the Ground Array

Buried scintillator detectors near the SD stations

- 750 and 433 m spacing





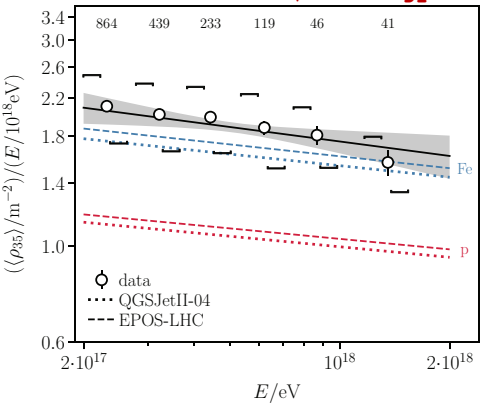


2.3 m depth provide $\sim 550\ \mathrm{g\ cm^{-2}}$ extra shielding

Direct measurement of the muon content

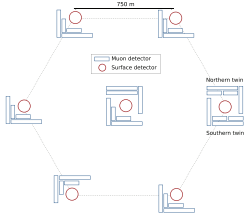
Auger Muons and Infill for the Ground Array - Engineering Array

Within LHC $\sqrt{s}$ energy!!



Data set:

- 1742 AMIGA EA events
- 2×10^{17} - 2×10^{18} eV
- October 2015 - October 2016
- $\theta < 45°$



AMIGA
Engineering Array

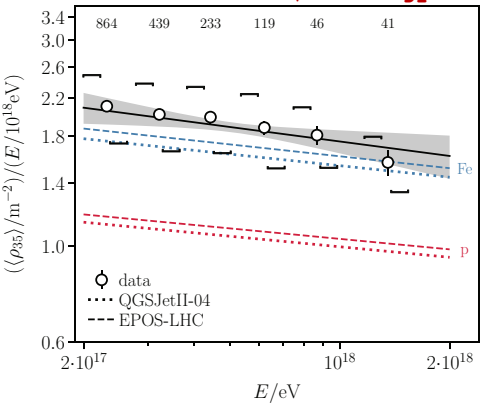
- Muon deficit in simulations of 8% (14%) for EPOS-LHC (QGSJetII-04) assuming pure iron composition

Eur. Phys. J. C 80 (2020) 751

Direct measurement of the muon content

Auger Muons and Infill for the Ground Array - Engineering Array

Within LHC $\sqrt{s}$ energy!!



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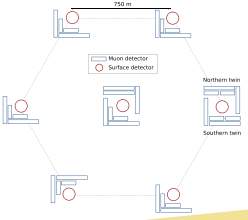


- Muon deficit in simulations of 8% (14%) for EPOS-LH
  assuming pure iron composition

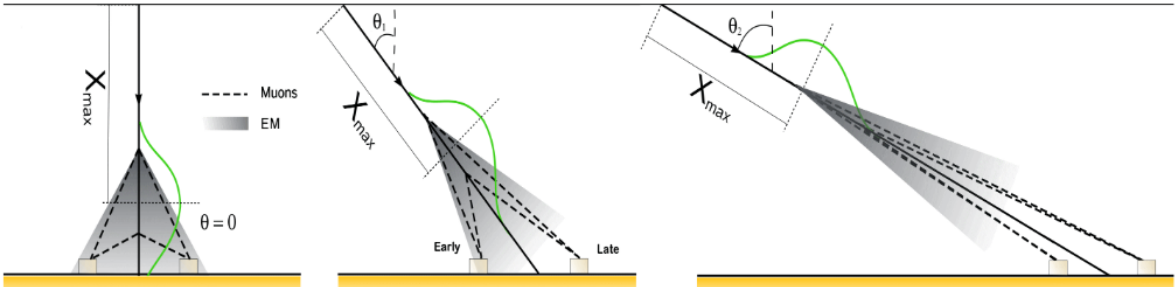
See talk tomorrow by:
Belén Andrada

Eur. Phys. J. C 80 (2020) 751

Horizontal Air Showers

Indirect muon measurements using the SD array

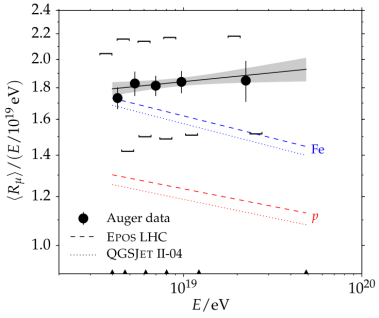
$\theta = 0°$ $X \sim 900 g/cm^2$ $\theta = 60°$ $X \sim 1800 g/cm^2$ $\theta = 80°$ $X \sim 5180 g/cm^2$

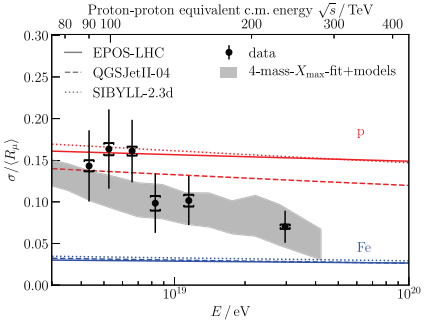


- **Interaction lengths rapidly increase for horizontal air showers**
  - **electromagnetic component heavily suppressed by the amount of atmospheric density traversed**

Muon measurements from Horizontal Air Showers

Indirect muon measurements using the SD array





Data set:

- 174 (281) Golden hybrid events
- $E > 4 \times 10^{18}$ eV
- 1 January 2004 - 1 January 2013 (31 December 2017)
- $62° < \theta < 80°$

Phys. Rev. D 91 (2015) 032003; Phys. Rev. Lett. 126 (2021) 152002
Errata: Phys. Rev. D 91 (2015) 059901

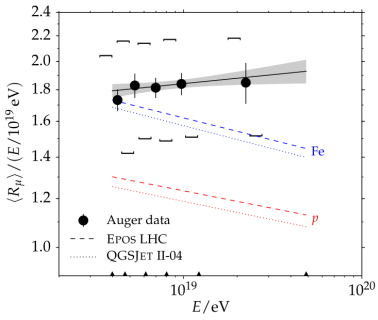
Two possible explanations:

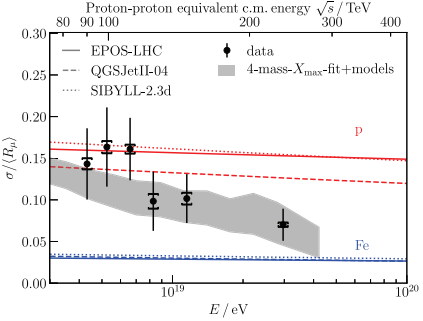
1. Increase in the muon content may be due to small modifications in hadronic interactions accumulating over many generations
2. Very particular modification of the first interaction changing $\langle R_\mu \rangle$ without affecting $\sigma / \langle R_\mu \rangle$

Phys. Lett. B 784, (2018), 68

Muon measurements from Horizontal Air Showers

Indirect muon measurements using the SD array





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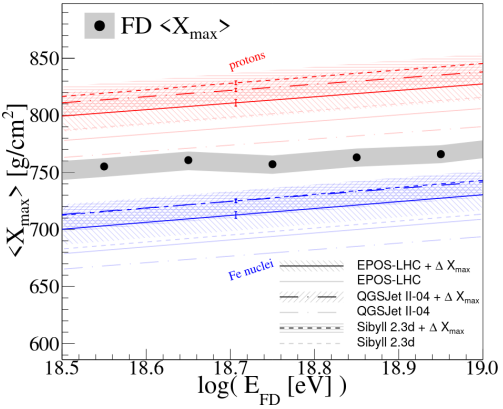
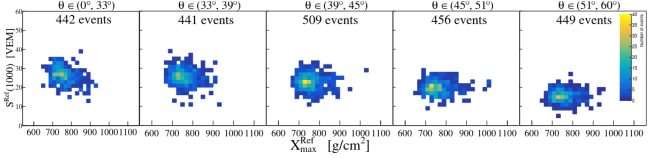
See talk tomorrow by: Belén Andrada

Phys. Lett. B 784, (2018), 68

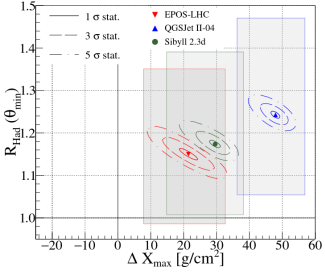
Simultaneous scaling of the muon content and X_{max}

Best fit of Auger hybrid data





Two dimensional distributions of S(1000) and X_{max} for different zenith angle bins

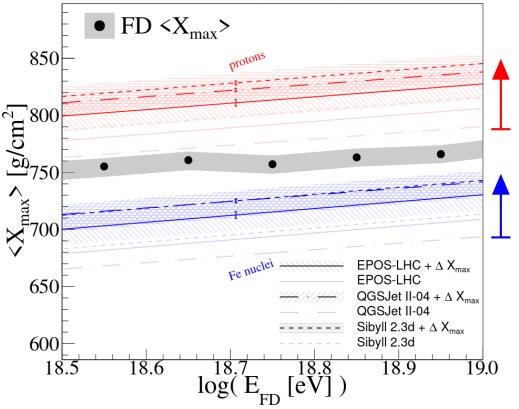


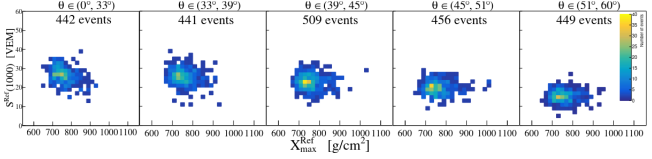
Data set:

- 2297 Golden hybrid events
- $10^{18.5}$ - 10^{19} eV
- 1 January 2004 - 31 December 2018
- $\theta < 60°$

Simultaneous scaling of the muon content and X_{max}

Best fit of Auger hybrid data





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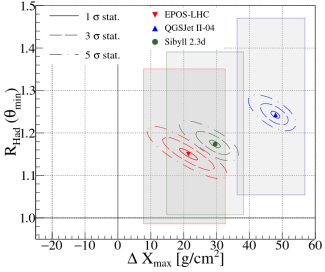


Data set:

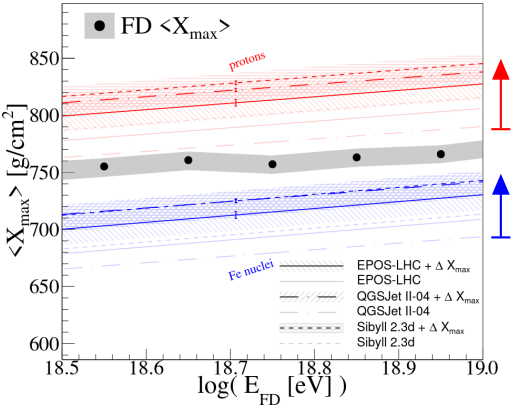
- 2297 Golden hybrid events
- $10^{18.5}$ - 10^{19} eV
- 1 January 2004 - 31 December 2018
- $\theta < 60°$

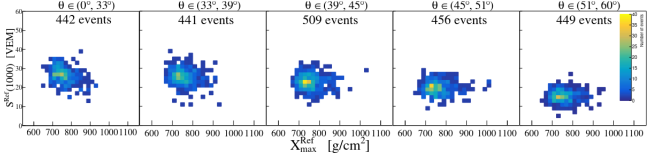
- Auger data best described if models predict deeper X_{max} values
  - Leading to a smaller muon deficit in simulations (and heavier mass composition)

PoS(ICRC2021), 310, (2021)

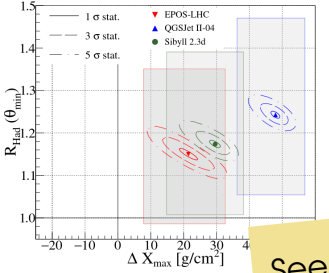
Simultaneous scaling of the muon content and X_{max}

Best fit of Auger hybrid data





Two dimensional distributions of S(1000) and X_{max} for different zenith angle bins



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- 1 January 2004 - 31 December 2018

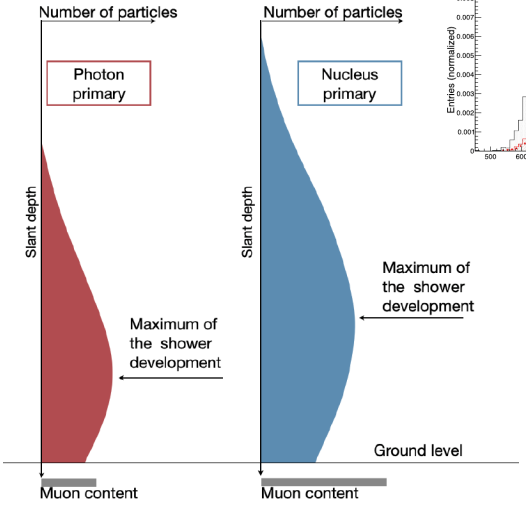
- Auger data best described if models predict deeper X_{ma}
  - Leading to a smaller muon deficit in simulations (an

See talk tomorrow by: Belén Andrada

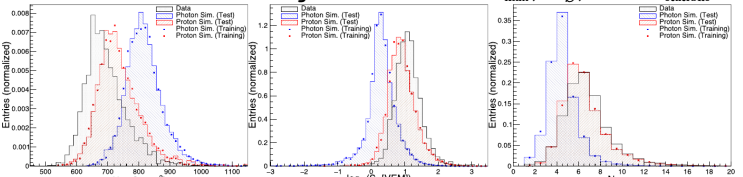
Neutral particles

Photon searches

We use several analyses and search methods

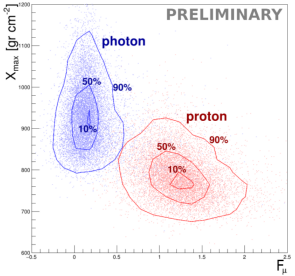


Multi-Variate Analysis with Boost Decision Tree of three discriminating observables: $X_{\max}$, S_b, and N_{stations}



The Astrophysical Journal 933 (2022) 125

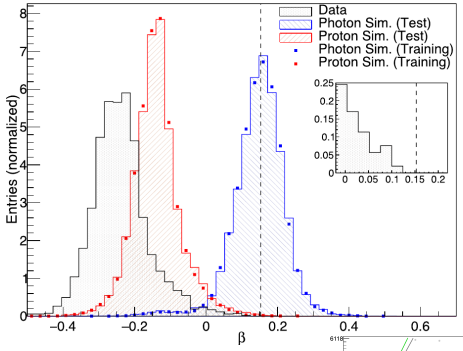
Fisher-Discriminant Analysis of estimated muon content F_μ and $X_{\max}$

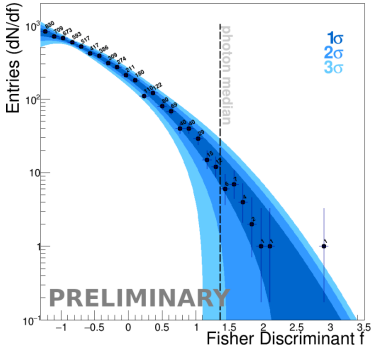


PoS(ICRC2021), 373, (2021)

Universe 8 (2022) 579

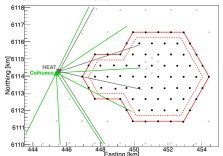
Searches for a diffuse flux of UHE photons





Data set:

- 2204 HeCO hybrid events
- $E \geq 2 \times 10^{17}$ eV
- 1 June 2010 - 31 December 2015

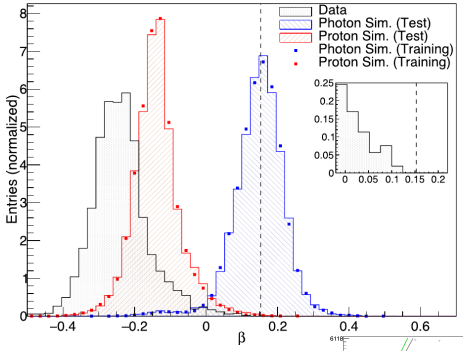


Data set:

- $>$ 32000 hybrid events
- $E > 10^{18}$ eV
- 1 January 2005 - 31 December 2017
- $\theta < 60°$

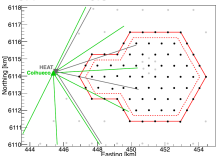
Searches for a diffuse flux of UHE photons

0 candidates



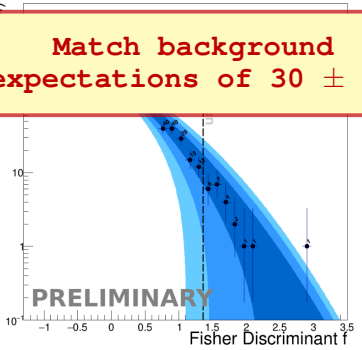
Data set:

- 2204 HeCO hybrid events
- $E \geq 2 \times 10^{17}$ eV
- 1 June 2010 - 31 December 2015



22 candidates

Match background expectations of 30 ± 15



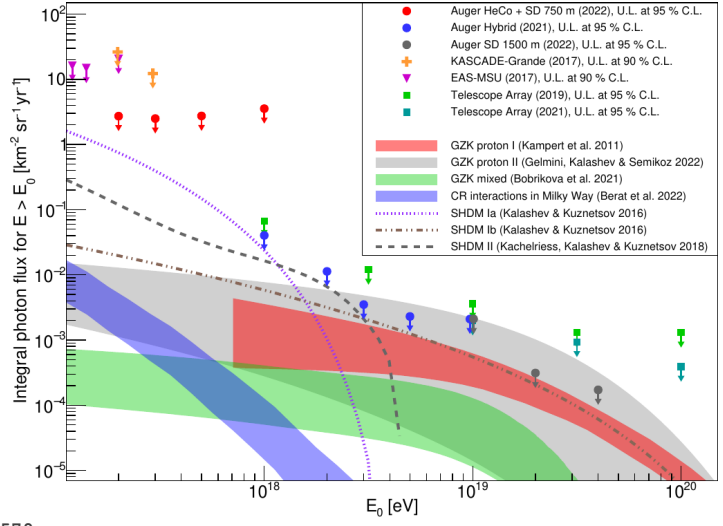
Data set:

- $>$ 32000 hybrid events
- $E > 10^{18}$ eV
- 1 January 2005 - 31 December 2017
- $\theta < 60°$

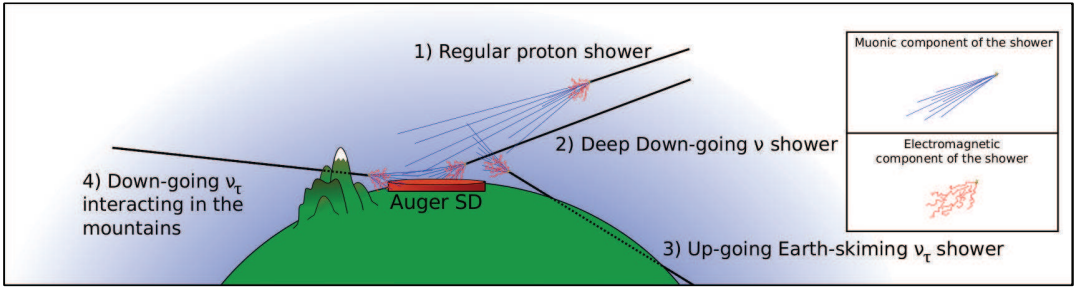
The Astrophysical Journal 933 (2022) 125 PoS(ICRC2021), 373, (2021)

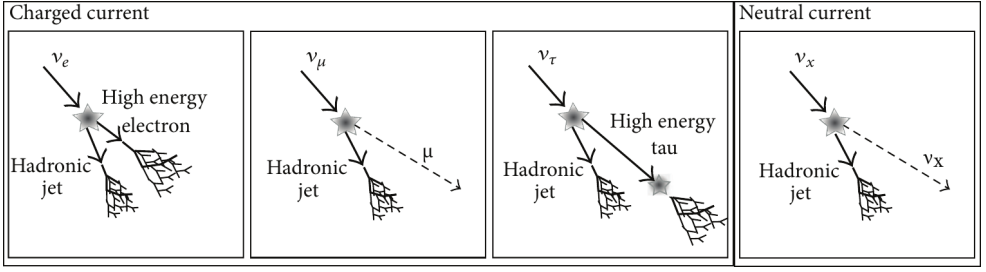
Searches for a diffuse flux of UHE photons - Results

No photons were found for $E > 2 \times 10^{17}$ eV



Neutrino searches

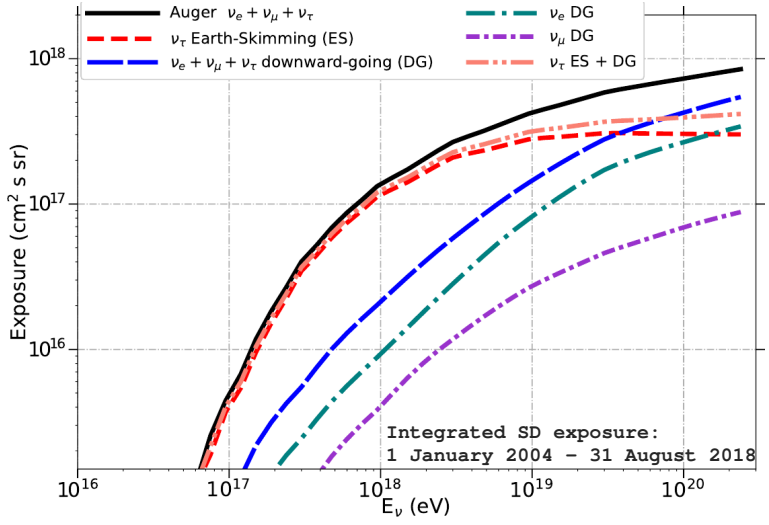




Phys. Rev. D 91, 092008 (2015)

Auger exposure to neutrino showers

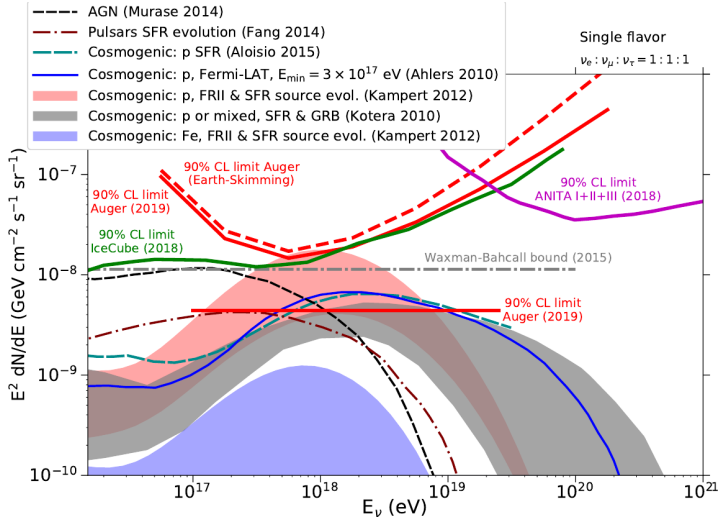
SD array is sensitive to neutrinos of any flavor with $E > 0.1$ EeV and $\theta > 60°$



JCAP 10 (2019) 022

Searches for a diffuse flux of UHE neutrinos

No neutrinos observed at 90% C.L.



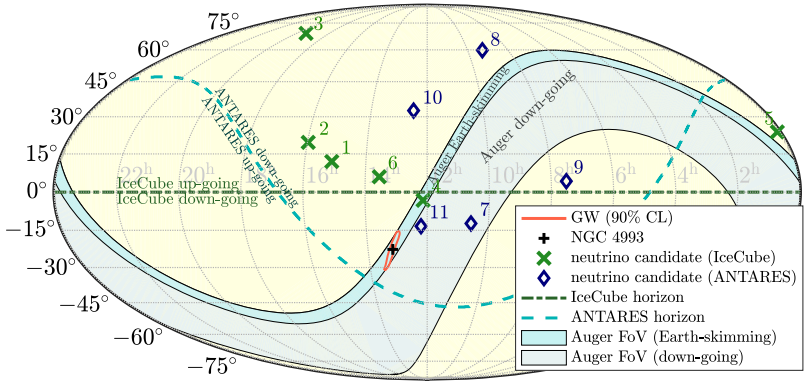
JCAP 10 (2019) 022

Multimessengers

Auger follow-up of Gravitational Wave events

We search for UHE neutrinos and photons from GW events

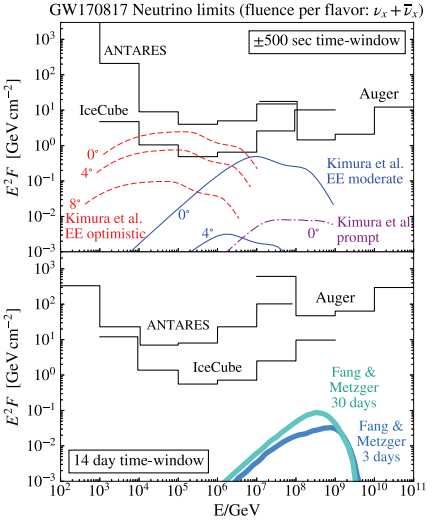
GW170817/GRB 170817A – Neutron Star merger, $D_s \simeq 40$ Mpc



Our best event so far

Phys. Rev. D 94 (2016) 122007
Astrophys. J. Lett. 848 (2017) L12
Astrophys. J. Lett. 850 (2017) L35
PoS(ICRC2021), 968, (2021)
PoS(ICRC2021), 973, (2021)

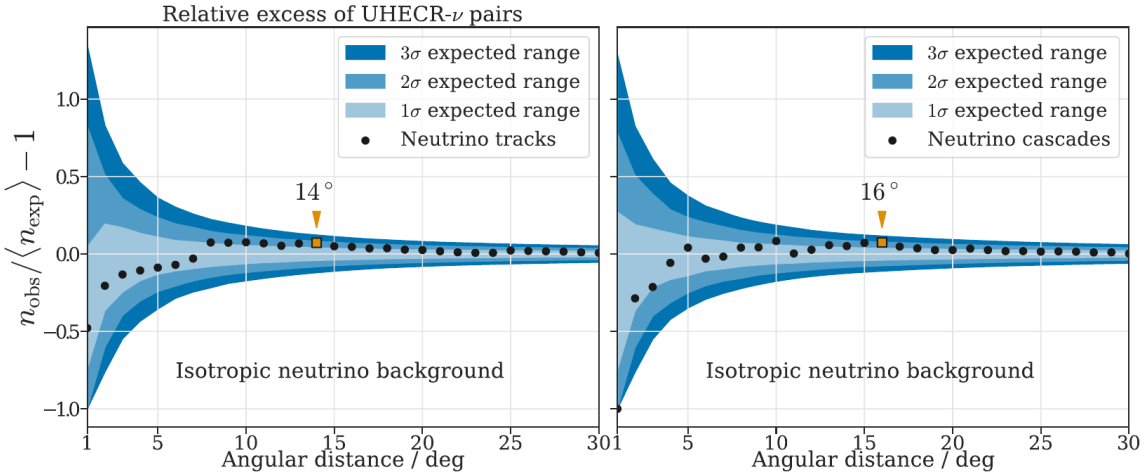
Auger neutrino follow-up of GW170817/GRB170817A



- GW170817/GRB 170817A location in the region of most sensitivity to UHE ν_τ in Auger
- Observations spanned over the $\pm$ 500 s time window and the 14 day period after it
- Good stability of the SD array during the $\pm$ 500 s period
  - $\sim$ 95.8 $\pm$ 0.1% of the 1660 stations were active
- **No inclined showers in the $\pm$ 500 s time window**
- **No neutrino candidates identified in the following 14 days**

Astrophys. J. Lett. 848 (2017) L12
Astrophys. J. Lett. 850 (2017) L35

Correlation of IceCube ν with Auger and TA UHECRs



No significant correlation between the arrival direction of neutrino point sources with of ultra-high-energy cosmic rays

The Astrophysical Journal 934 (2022) 164

AugerPrime

AugerPrime

Upgrades:

- **SSD – Scintillator Surface Detector**
  Enhance the separation of electron / muon components (for $\theta < 50°$)
- **RD – Radio Detector**
  Enhance the separation of electron / muon components (for $\theta > 50°$)
- **UMD – Underground Muon Detector**
  Direct muon counting at 0.1 $\mathrm{EeV} < E < 10$ EeV
- **SDEU – Surface Detector Electronics Upgrade**
  Increased sampling rate, timing accuracy and higher dynamic range
- **Enhanced FD duty cycle**
  15% to 25% extension in the FD operating time to increase statistics at the highest energies

Objectives:

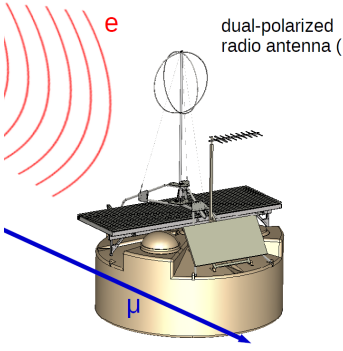
- Composition sensitivity in the flux suppression region
- Sensitivity to 10% proton fraction at $E > 10$ EeV (important for GZK photon and neutrino fluxes)
- Composition enhanced anisotropy studies
- Search for new phenomena in hadronic interactions

The Pierre Auger Observatory Upgrade – Preliminary Design Report, [arXiv: 1604.03637]
Science Reviews – from the end of the world (Argentina) 1 (2020) 4:8–33

AugerPrime

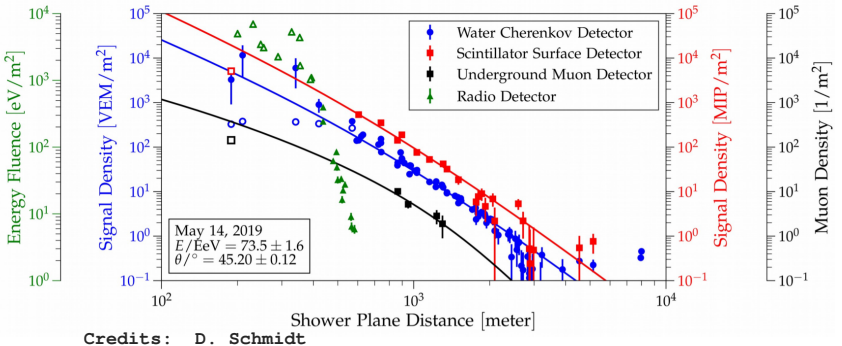
Enhanced sensitivity to event-by-event nuclear mass composition

- Improved EM / μ separation using the SSD and RD



Credits: F. Schlüter

Multi-hybrid events

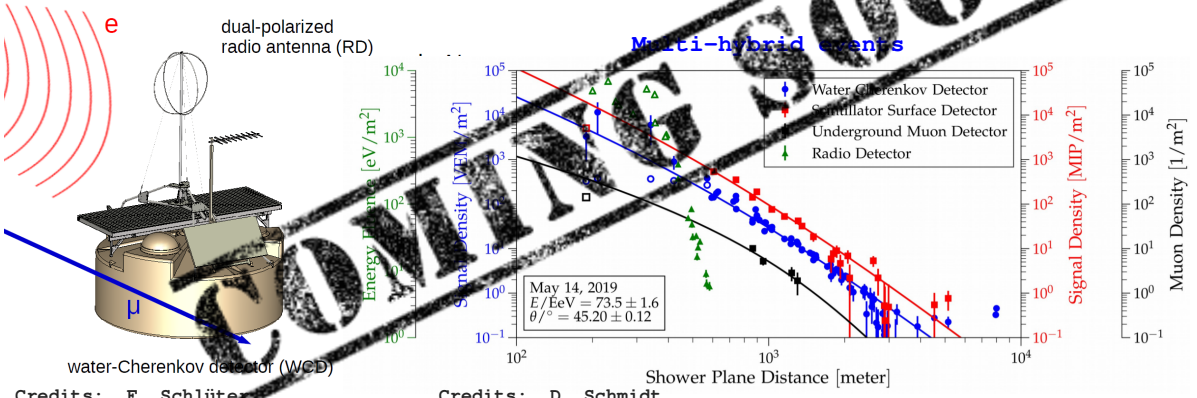


Credits: D. Schmidt

AugerPrime

Enhanced sensitivity to event-by-event nuclear mass composition

- Improved EM / μ separation using the SSD and RD



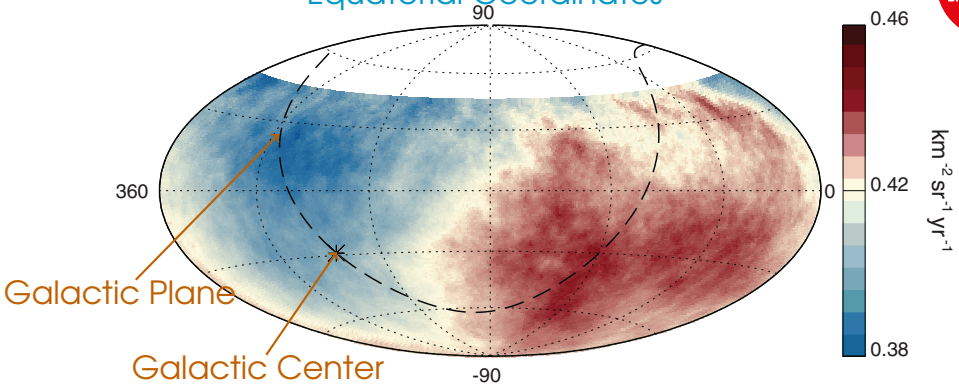
COMING SOON


Thank you very much
for your attention!
Any questions or comments?


Backup slides

Observation of large scale anisotropy for $E > 8$ EeV (III)

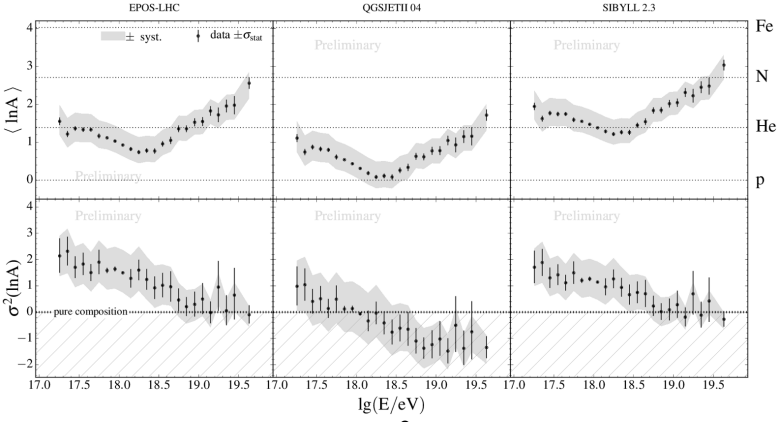
Highest energy cosmic rays have extragalactic origin!



- Dipole became more significant with increasing exposure
- Maximum modulation at $(\alpha_d, \delta_d) = (100°, -24°)$
  - $\sim 125°$ away from the Galactic Center

Science 357 (2017) 1266–1270

First and second X_{max} moments

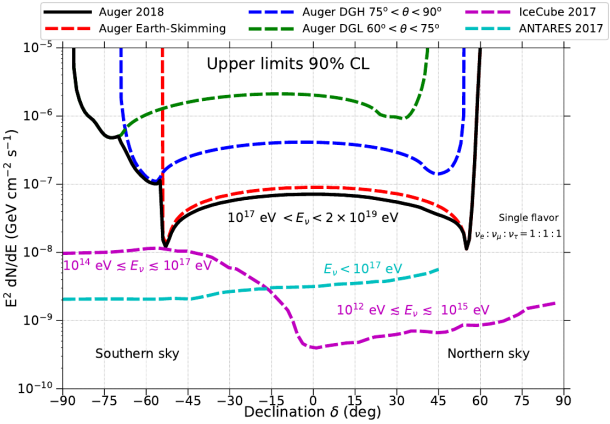


- Negative values for $\sigma^2(\ln A)$ are not physical
  - Models predict larger $\sigma(\ln A)$ than the measured ones
- EPOS-LHC is the model which **best** describes data

Phys. Rev. D 90 (2014) 122006
PoS(ICRC2017), 506, (2017)

Searches for a point-like sources of UHE neutrinos

No neutrinos observed at 90% C.L.

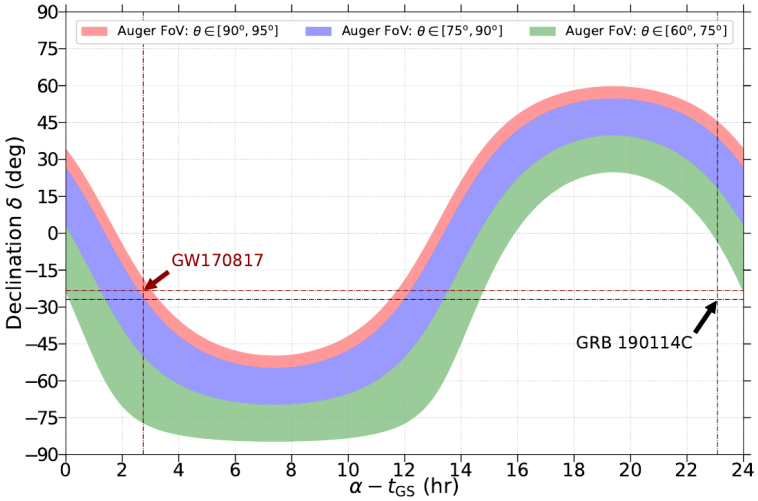


Auger sensitivity to neutrinos is comparable to other neutrino experiments:

- Maximum sensitivity at EeV where most cosmogenic models also peak
- Limits are $\sim$ 4 times below the Waxman-Bahcall bound on ν production in optically thin sources

JCAP 10 (2019) 022

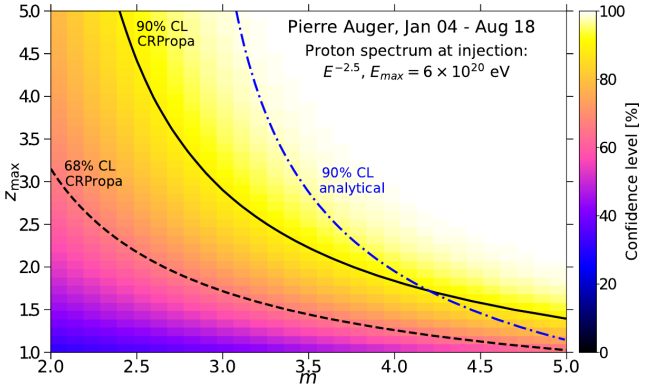
Neutrino sensitivity to GW170871 and GRB190114C



JCAP 10 (2019) 022

Limits to cosmogenic neutrino fluxes

No neutrinos observed at 90% C.L.

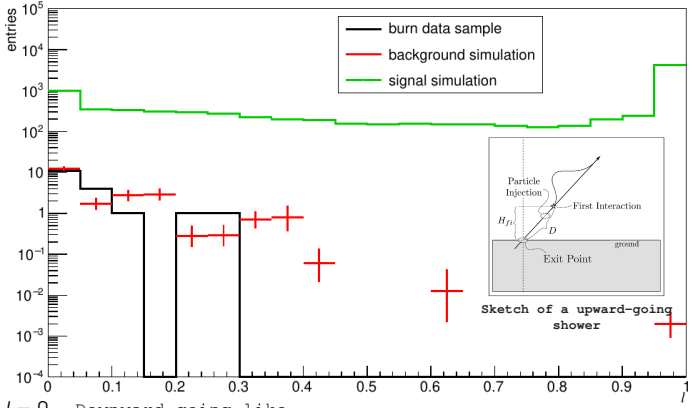


Auger sensitivity to neutrinos is comparable to other neutrino experiments:

- Some models of ν production in AGNs excluded at $> 90\% C.L.$
- Large range of exotic models of ν production excluded with $> 99\% C.L.$
- Several cosmogenic ν models assuming pure proton composition are disfavored

JCAP 10 (2019) 022

Searches for upward-going showers using the FD



$l = 0$ - Downward-going like
$l = 1$ - Upward-going like

Data set:

- 14 years FD operation
  - Monocular mode - no SD information
- $E_{cal} = 10^{16.5}$ - $10^{18.5}$ eV

Background:

- Laser shots
  - Used for FD calibration
- Misreconstructed downward-going events

1 candidate survived all the cuts

$n_{bkg} = 0.45 \pm 0.18$

$$F^{95\%}_{\gamma=1}\left(E_{\rm cal} > 10^{17.5}\,{\rm eV}\right) = 3.6 \times 10^{-20}\ {\rm cm^{-2}\ sr^{-1}\ s^{-1}}$$

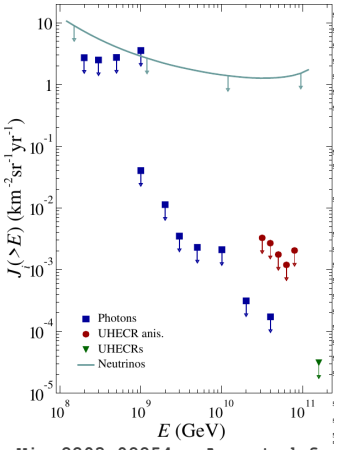
$$F^{95\%}_{\gamma=2}\left(E_{\rm cal} > 10^{17.5}\,{\rm eV}\right) = 8.5 \times 10^{-20}\ {\rm cm^{-2}\ sr^{-1}\ s^{-1}}$$

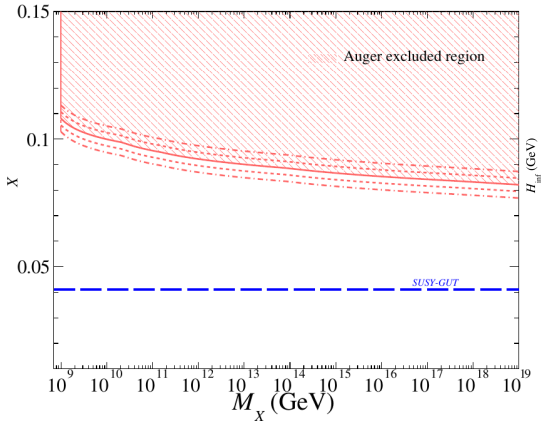
PoS(ICRC2021), 1140, (2021)

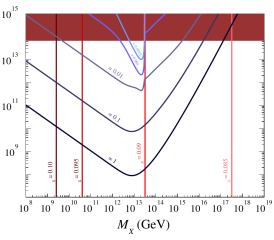
Secondary by-product fluxes from SHDM decay

Upper limits to Planckian-interacting massive Dark Matter

A clustering of UHE photons clustering in the direction of the Galactic center could hint to the existence of super-heavy relics decaying now





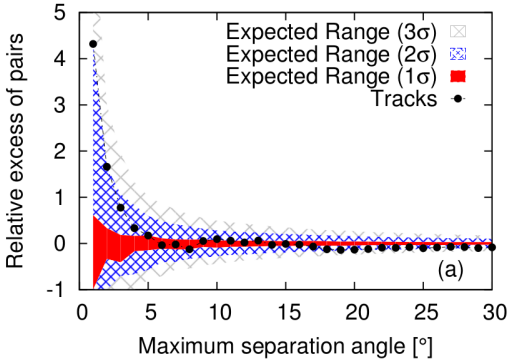


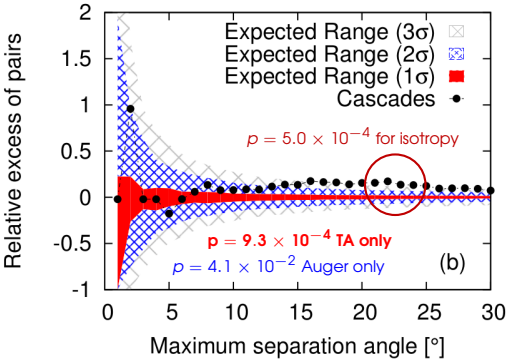
arXiv:2203.08854 – Accepted for publication in PRL

arXiv:2208.02353 – Accepted for publication PRD (accompanying paper to the PRL)

Correlation of IceCube ν with Auger and TA UHECRs

IceCube high-energy track-like and cascade events





- Most excess near the Super-Galactic plane and at the TA 'hot-spot' $(l, b) \simeq (177°, 50°)$
- Another excess of events observed in the Cen A direction

Excess disappeared in updated analysis

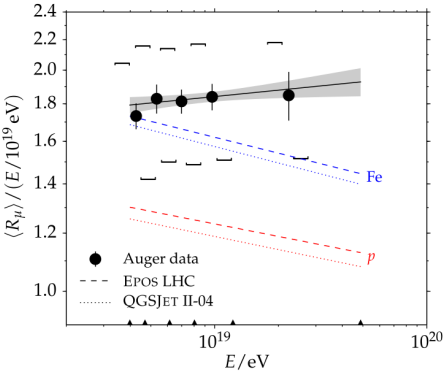
JCAP 01 (2016) 037

The Astrophysical Journal 934 (2022) 164 – Update

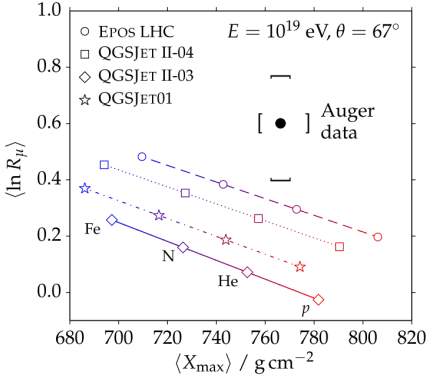
Muon content from Horizontal Air Showers

174 Golden hybrid events collected between 1 January 2004 and 1 January 2013

- $E > 4 \times 10^{18}$ eV
- $62^\circ < \theta < 80^\circ$



$\langle R_\mu \rangle$ higher than model predictions for pure iron!



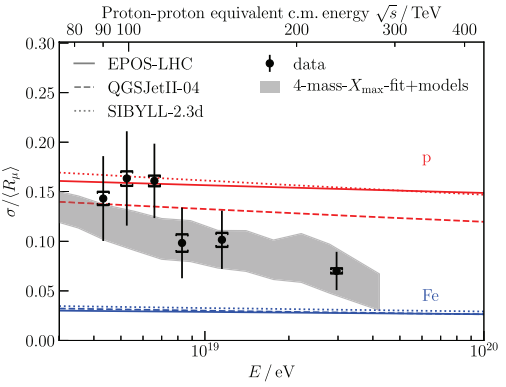
Tension between $\langle X_{\max} \rangle$ and $\langle \ln R_\mu \rangle$ measurements

Phys. Rev. D 91 (2015) 032003; Errata: Phys. Rev. D 91 (2015) 059901

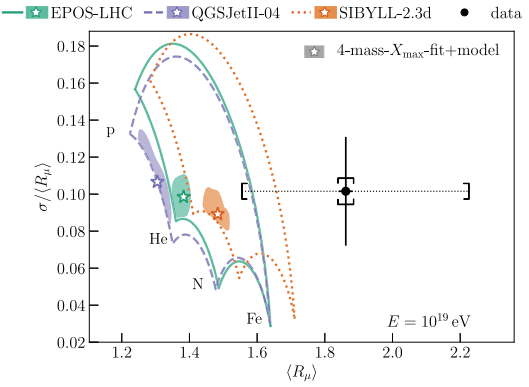
Muon fluctuations from Horizontal Air Showers

281 Golden hybrid events collected between 1 January 2004 and 31 December 2017

Same selection criteria of Phys. Rev. D 91 (2015) 032003!



Data falls between model predictions



Increase of $\langle \ln R_\mu \rangle$ between 26% for Sibyll 2.3d and 43% for QGSJetII-04

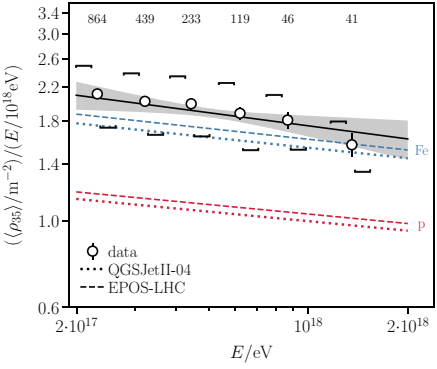
Phys. Rev. Lett. 126 (2021) 152002

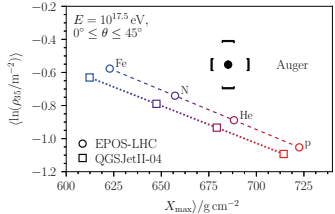
Direct measurement of the muon content

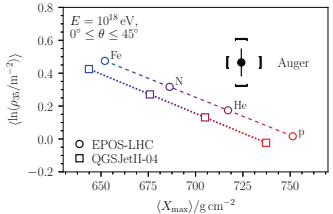
1742 events collected between October 2015 and October 2016

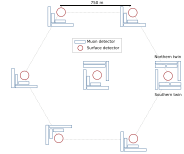
- 2×10^{17} eV $< E < 2 \times 10^{18}$ eV
- $\theta \leq 45°$

Within LHC $\sqrt{s}$ energy!!







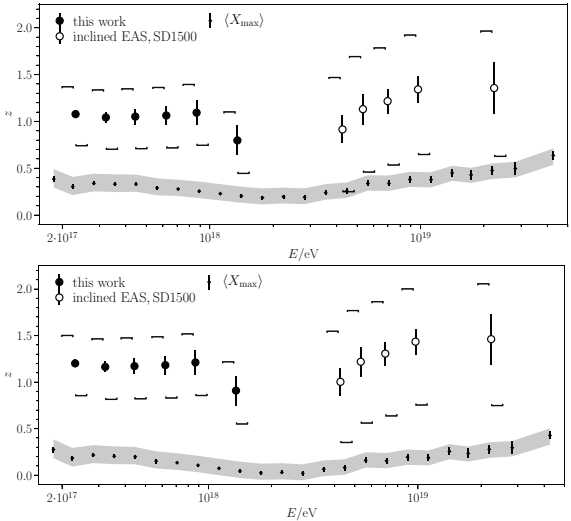


AMIGA
Engineering Array

- Muon deficit in simulations of 8% (14%) for EPOS-LHC (QGSJetII-04) assuming pure iron composition
- Pure iron composition within systematic uncertainties

Eur. Phys. J. C 80 (2020) 751

Comparison - Muon content measurements



Phys. Rev. D 91 (2015) 032003; Errata: Phys. Rev. D 91 (2015) 059901
Eur. Phys. J. C 80 (2020) 751